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Multi-band Carrier-less Amplitude and Phase Modulation for Bandlimited Visible Light Communications Systems

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***Abstract*—Visible light communications (VLC) is a technology with enormous potential for a wide range of applications within next generation transmission and broadcasting technologies. VLC offers simultaneous illumination and data communications by intensity modulating the optical power emitted by light-emitting diodes (LEDs) operating in the visible range of the electromagnetic spectrum (∼370 – 780 nm). The major challenge in VLC systems to date has been in improving transmission speeds, considering the low bandwidths available with commercial LED devices. Thus, to improve the spectral usage, the research community has increasingly turned to advanced modulation formats such as orthogonal frequency division multiplexing. In this article we introduce a new modulation scheme into the VLC domain; multi-band carrier-less amplitude and phase modulation (*m*-CAP) and describe in detail its performance within the context of bandlimited systems.**

***Index Terms*—Bit error rate, light emitting diodes, carrier-less amplitude and phase modulation, visible light communications**

I. Introduction

ADVANCED modulation formats are becoming increasingly important in visible light communications (VLC) systems [1, 2] utilising light-emitting diode (LED) based lighting infrastructure. One of the primary aims of VLC is to provide high capacity broadcasting networks to next generation smart homes and offices, whilst simultaneously providing full room illumination. Therefore, one of the key challenges associated with VLC concerns the bandwidth limitation associated with commercial white LEDs, which behave as first order low-pass filters [3, 4]. White light is produced using blue LEDs coated in yellow colour converting phosphor. Even though the blue LEDs offer bandwidths in the order of tens of MHz, the colour converting phosphor substantially reduces this to just a few MHz, thus imposing a large impediment to achieving high speed networks. A straightforward method to combat the bandwidth limitation of LEDs is to employ appropriate power pre-emphasis techniques [2]. However, using power equalization will introduce additional signal distortion due to the nonlinear effects of the LEDs [5], thus limiting the achievable performance gain. As a result, achieving high capacities has been a major challenge for researchers working in this field.

In recent years, orthogonal frequency division multiplexing (OFDM) has been the focus of enormous attention due to its ability to support spectrally efficient and high order modulation formats such as quadrature amplitude modulation (QAM) and efficiently overcome the distortion imposed by bandwidth limitation or non-flat fading. This enables an improvement in power and spectral usage over more traditional formats such as on-off keying (OOK), thus resulting in increased transmission speeds. For instance, transmission speeds in the region of 1 Gb/s/wavelength have been reported in [1] by optimizing the OFDM modulation format using adaptive bit- and power-loading, while speeds in the order of hundreds of Mb/s have been achieved using OOK [4]. Adaptive loading techniques operate by adjusting the number of bits-per-symbol and power-per-subcarrier according to the measured error vector magnitude (EVM) at the receiver.

Regardless of the increased popularity of OFDM, researchers are searching for alternative modulation formats. New multi-carrier techniques have been considered recently to save system bandwidth in optical communications by compressing the sub-carrier spacing. Fast OFDM [6], spectrally efficient frequency division multiplexing [7] and faster than Nyquist [8] have all been studied and demonstrated for use in optical communications, resulting in up to 50% bandwidth savings. However, complexity remains an issue that has to be resolved before these systems can be adapted to VLC. The other important issue that needs to be addressed is power efficiency, since OFDM VLC systems exhibit an inherent high peak-to-average power ratio (PAPR) and suffer from nonlinear distortions due to the limited dynamic range of optical sources. Several authors proposed more power efficient schemes like

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low PAPR single carrier frequency-domain equalization (SC-FDE) [9]. Here the IFFT block was moved from the transmitter to the receiver side avoiding the generation of complicated waveforms and consequently reducing PAPR. Further improvement of the spectral efficiency have been reached by novel OFDM SC-FDE signal formats - polar OFDM and polar SC-FDE in [10]

Currently, one of the most novel and popular modulation formats is carrier-less amplitude and phase modulation (CAP), which has been experimentally shown to offer improved transmission speeds in comparison to OFDM when utilizing the same physical link, but with potentially high implementation cost using existing DSP hardware [1]. This is significant, as CAP modulation is relatively simple to implement in real time. In CAP the carrier frequencies are generated using finite impulse response (FIR) filters, where most of the complexity is introduced depending on the filter length, while the most computationally complex components is the digital-to-analogue converter module. On the other hand, OFDM requires the use of inverse and forward fast Fourier transforms, which can be also computationally costly, depending on the required number of subcarriers.

Unfortunately, to the authors' knowledge, CAP has only been tested in the case of flat-band magnitude responses, which is a phenomenon that is seldom available in VLC, due to the low modulation bandwidths available from the LEDs; refer to Fig. 4(b) of [11]. Despite CAPs advantages, its candidature as a promising format for generic VLC systems is questionable. OFDM can be tailored to any frequency response using bit-loading algorithms, unlike CAP which must have a fixed modulation order cardinality. In [12] a solution to this problem was proposed for optical fibre links. The gross transmission bandwidth was divided into six sub-bands (or subcarriers, for consistency with OFDM nomenclature), relaxing the condition for a flat-band response and allowing the number of bits/symbol to be adjusted for each subcarrier.

Based on this, it follows that additional performance can be gained by increasing the number of subcarriers towards m, thus the concept of m-CAP, as the decreasing subcarrier bandwidth approximate towards flat-bands. This is a substantial advantage for VLC systems which rarely exhibit flat-band responses, as can be referred to in the literature, i.e. Fig. 4(b) of [11] which shows a high attenuation outside of the modulation bandwidth. Having an approximately flat-band response means the frequency dependent attenuation is minimized and hence an increasing order of m should offer continuous improvements in terms of power penalty and bit error rate performance. On the other hand, by increasing to m subcarriers, the FIR filter requirement scales up to $2m$ and consequently the relative computational complexity is increased accordingly. Simultaneously, [12] showed that with increasing m; the required sampling frequency approaches the Nyquist rate, which is a significant and unexpected advantage.

In Fig. 1 the concept of m-CAP is illustrated for $m = 1,\ 2,$ and 10. By increasing m, the subcarrier bandwidth is reduced, thus offering additional protection to attenuation caused by the low-pass LEDs in comparison to the high bandwidth subcarriers (i.e. low m). Therefore there is a trade-off between complexity and performance as in OFDM systems. The objective of this article is not to analyse the relative computational complexities between OFDM and m-CAP and hence this discussion is left open for research. In this article, we propose m-CAP as a standalone modulation format for VLC and consider its performance for a bandlimited LED system. The proposed system is studied using realistic system and device models and verified through numerical simulations.

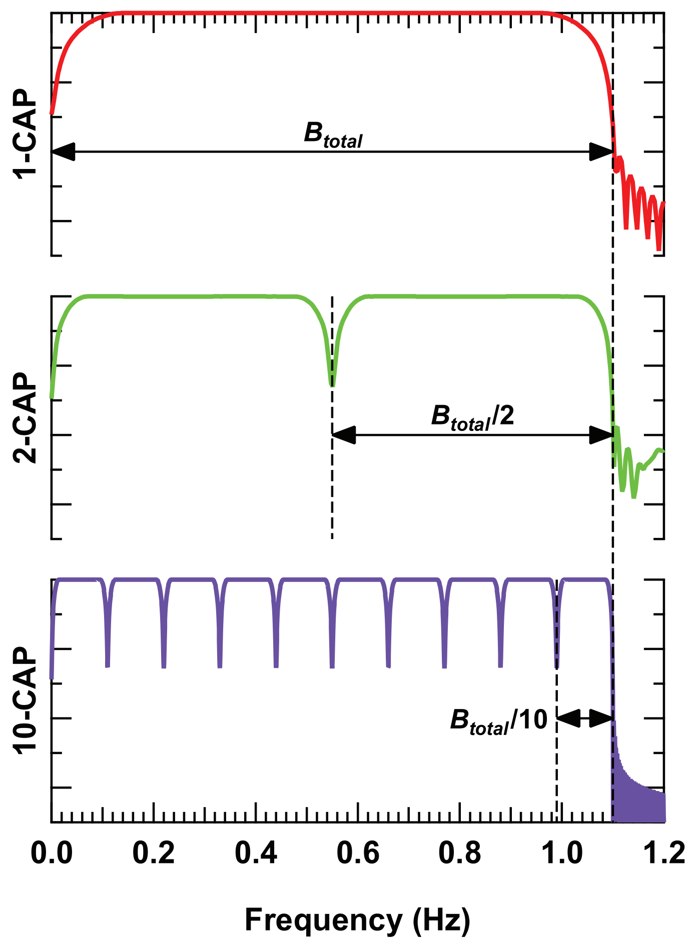

Fig. 1. The concept of m-CAP illustrated in terms of the frequency response for several values of m. It should be noted that B_{total} indicates the system bandwidth as will be discussed

II. m-CAP Modulation for VLC

A block diagram for an m-CAP VLC system is illustrated in Fig. 2.

A. m-CAP Generation

In this section a description on m-CAP generation is provided. First, m independent data streams D_m are generated and mapped into the QAM constellation (Fig. 2(a)). Here 16-QAM will be considered to illustrate the concept. The choice of constellation cardinality is insignificant as without any loss of generality, the ensuing discussion is valid across every order of QAM. The data is up-sampled by means of zero padding by a number of samples per symbol N_{ss} in order to match the system sampling frequency before the real $\Re$ and imaginary $\Im$ components of the modulated data are isolated. The

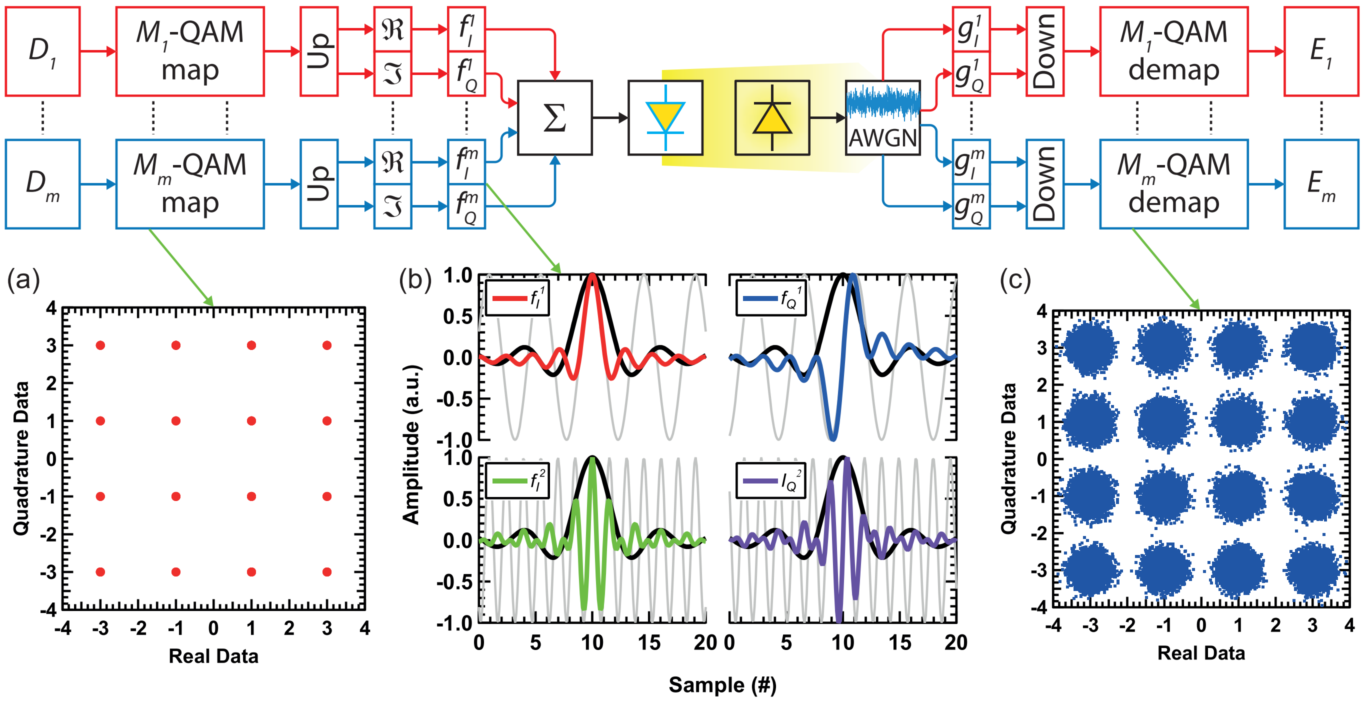

Fig. 2. The schematic block diagram of the proposed system. It should be noted that in (b) the impulse responses displayed are for $m = 1$ and 2 at the minimum carrier frequencies and variations on these pulse shapes are likely, depending on the desired carrier frequency

components are passed through real and imaginary transmit filters whose impulse responses form a Hilbert pair [12]. The impulses are found as the product of a cosine or sine (real or imaginary, respectively) with a root-raised cosine filter (RRCF) as shown in Fig. 2(b), while the analysis can be found in [13]). The minimum carrier frequency must be at least twice the RRCF pulse width. Clearly the carrier frequency of the subcarrier is controlled by the frequency of the (co)sine wave and hence is introduced by the FIR filters, unlike QAM, which requires a local oscillator. This is the main difference between the two formats and is a significant advantage of CAP, since incoherent time-reversed matched filters can be deployed at the receiver, eliminating the use of a complex phase locking circuit. The real and imaginary components are added prior to transmission via intensity modulation of the LED.

The required sampling frequency and number of samples-per-symbol can be referred to mathematically in the literature and hence are not shown here [12]. Considering the use of a RRCF, the minimum subcarrier bandwidth is controlled by the roll-off factor, β, as expected, which varies between $0 \leq \beta \leq 1$. A larger β means a $1+\beta$ greater bandwidth requirement as is illustrated in Fig. 3 for a normalised signal bandwidth. In this work we have set $\beta = 0.1$ due to (*i*) consistency with recent literature [12] and (*ii*) a lower β means a higher spectral efficiency can be achieved due to more effective spectral usage.

Further parameters adopted in this article as follows; the overall system baud rate is set to unity, meaning that each subcarrier has a baud rate of $1/m$. This condition ensures that the bandwidth remains constant regardless of m which is important when considering a bandlimited link as will be described in the following sentences. In order to examine the performance of m-CAP in terms of a bandlimited VLC system, two approaches can be adopted:

1) Maintaining a constant -3 dB modulation bandwidth and increase the overall baud rate.
2) Maintaining a constant overall unity baud rate and vary the LED low-pass cut-off frequency.

In this article we adopt the latter approach for simplicity, and hence the overall baud rate is selected as unity throughout. Therefore, recalling the selection of $\beta = 0.1$, the total bandwidth requirement is calculated as 1.1 Hz as is shown in Fig. 4.

In general, LEDs exhibit a non-linear electro-optic response (i.e. current to optical power) [5], however this varies from device to device and from one model to the next [5]. For instance, polymer LEDs can display excellent linearity [11], while conventional devices can heavily distort the transmit signal [5] and thus a generalized solution is impossible to consider at this stage. As a result we select a perfectly linear electro-optic response in this article as it is not our intention to discuss this type of signal distortion concurrently with bandwidth distortion at this stage. If the non-linear properties were taken into account, the m-CAP system would still work, but may require customisation to the specific LED chosen. The signal propagates over the line-of-sight indoor channel (reported mathematically in [11]), excluding multi-path components, and is detected by an ideal positive-intrinsic-negative (p-i-n) photodiode.

B. Modulation Bandwidths

As reported in [4], the major impediment to achieving high transmission speeds in VLC is the slow temporal response of the yellow phosphor, limiting bandwidths to a few MHz.

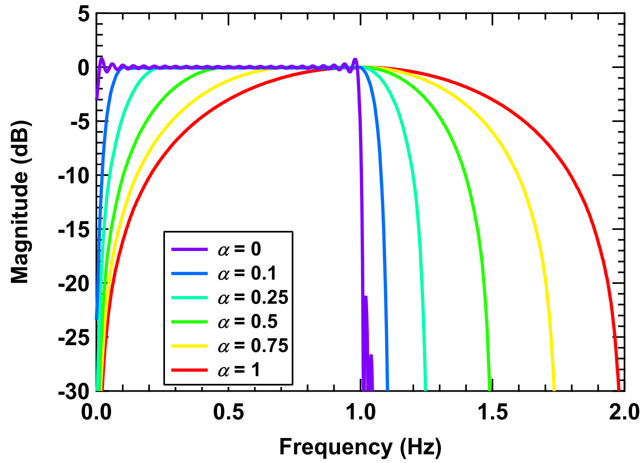

Fig. 3. 1-CAP pulse shapes considering a range of β

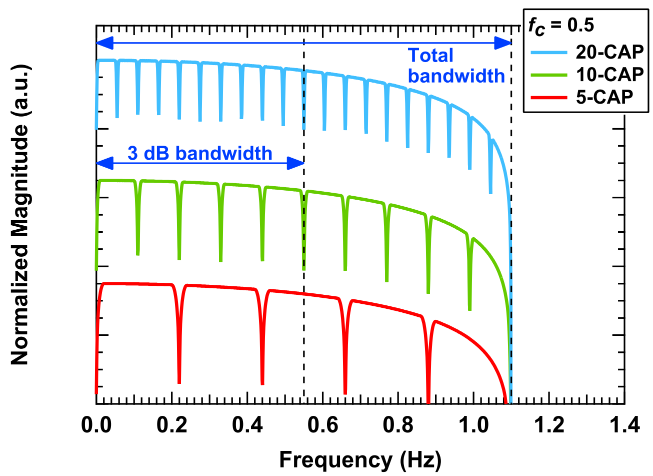

Fig. 4. Example frequency responses considering $f_c = 0.5$; note that the distortion on each subcarrier for high values of m is less than that for lower values of m

This means that achieving high transmission speeds is a considerable challenge facing the VLC research community. It is well known that the frequency response of LEDs can be modelled, as a good first approximation, by a first order low-pass filter [4], as the parasitic components will vary from device-to-device. For example polymer LEDs have substantially more parasitics (i.e. capacitance) than conventional inorganic devices. The LED bandwidths f_c under test are selected as a fraction of the overall 1.1 Hz signal bandwidth as follows: $f_c = \{0.1,\ 0.25,\ 0.5,\ 0.75,\ 0.9\}$. As an example, this means that when $f_c = 0.5$ the cut-off frequency of the LED is given by the ratio of the signal bandwidth to the LED bandwidth, i.e. $1.1/0.5 = 0.55$ Hz, as illustrated in Fig. 4 for 5-CAP, 10-CAP and 20-CAP.

It is clear from Fig. 4 that as the order of m increases (i.e. a higher number of subcarriers); each subcarrier suffers reduced distortion due to the attenuation as a result of the low pass filter in spite of the fact that the envelopes of each signal possess the same shape. The reason for this is that each subcarrier has a lower bandwidth requirement for higher orders of m-CAP and hence is less prone to attenuation induced distortion. It should be noted that there will be no improvement in the noise performance since the total signal power for every value of m is equal. Thus, it would be expected that additional transmission speed performance will be obtained when using higher values of m in bandlimited systems, at the cost of additional hardware complexity because of the increased requirement for FIR filters.

C. Receiver

At the receiver the sampling frequency should be equal to that at the transmitter, and hence needs to be set as described in [12], which shows that with an increasing value of m, the sampling frequency approaches the Nyquist limit. The implication of this is that when using m-CAP, available transmission speeds will at least equal to those available in conventional 1-CAP whilst using a lower sampling frequency that approaches the Nyquist limit. Thus the conditions for high speed digital-to-analogue converters are relaxed leading to reduced cost and complexity.

The dominant noise source present in the system is introduced by the receiver electronics and is modelled as additive white Gaussian noise (AWGN). Once more referring to Fig. 2, the received signal is split into $2m$ branches (real and imaginary for each m) and passed through reverse-time real and imaginary receiver filters matched to the transmit filters before down-sampling and constellation de-mapping (Fig. 2(c)) in order to provide an estimate of the symbols E_m for comparison with D_m in a symbol-by-symbol bit error rate (BER) measurement.

D. FIR Filters

Several advantages can be gained by dividing the desired transmission bandwidth into m subcarriers. The most important of which is that the attenuation observed over the signal frequencies due to the low pass filter is severely reduced due to the smaller subcarrier bandwidth requirements, as mentioned in the previous section. Therefore, here we examine the error performance across five different values of m (i.e. $m = \{1,\ 2,\ 5,\ 10,\ 20\}$), chosen to allow a large window of observation into any improvement. It should be noted that $m = 20$ corresponds to 40 FIR filters in the transmitter alone, and a further 40 in the receiver, amongst other resources. Therefore, the length of the filters is crucial; and hence studies have been performed that investigated the effect on varying lengths [14] and demonstrated improved BER performance with longer filter lengths. Depending on system requirements such as the target bit rate, BER or application, amongst others, 40 FIR filters could be considered excessive, depending on the available resources. Therefore, it is essential to keep in mind the trade-off between performance improvement and implementation complexity in m-CAP systems.

III. m-CAP Bit Error Rate Performance

A. Simple bandlimited m-CAP

The BER performance of the proposed bandlimited m-CAP systems are shown for $f_c = 0.5$ in Fig. 5(a)–(d), which show the performance of each subcarrier (denoted as s in Fig. 5)

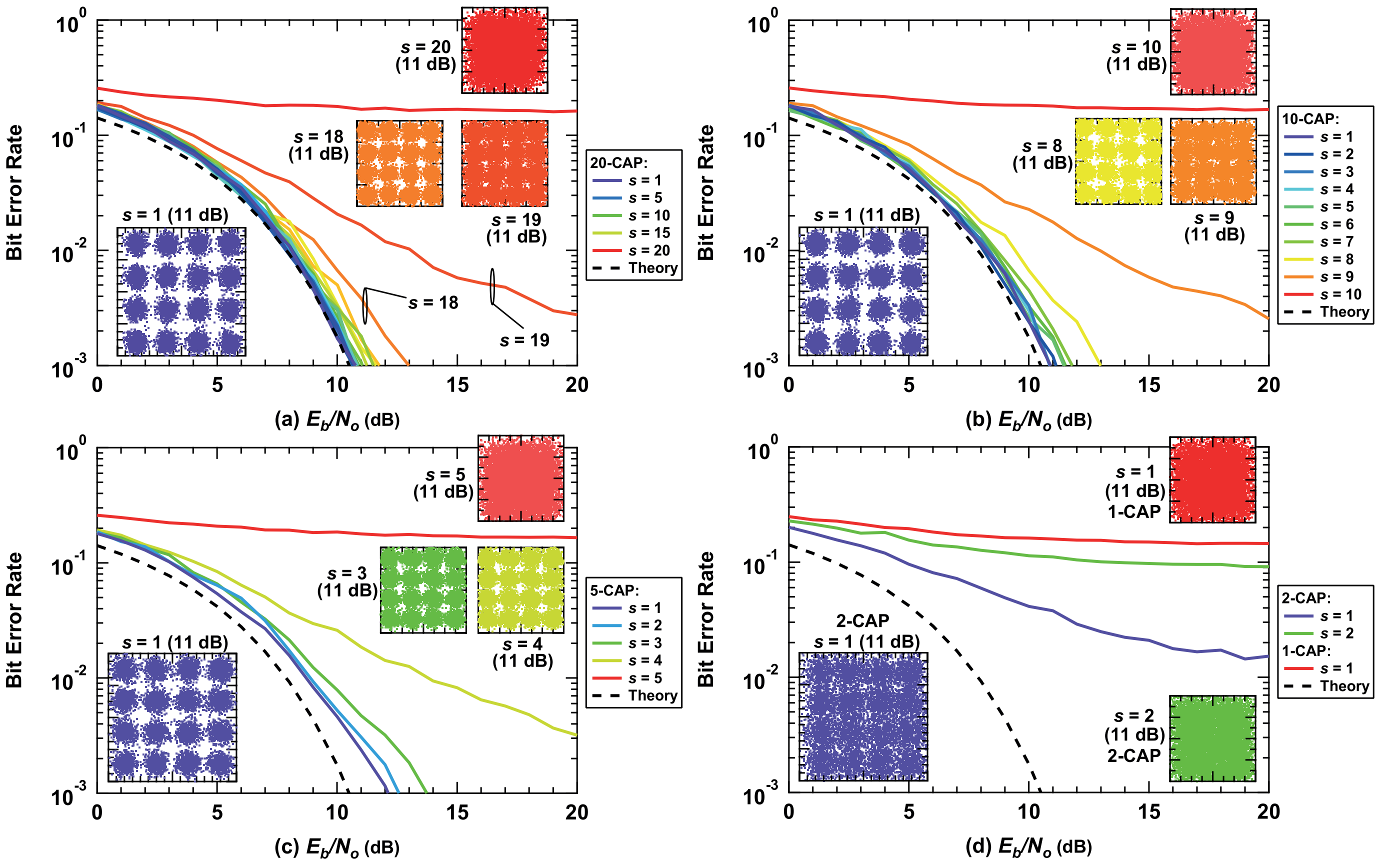

Fig. 5. BER performance as a function of SNR for $m =$ (a) $20,$ (b) $10,$ (c) 5 and (d) $\{2,\ 1\}$. Clearly the BER performance improves with increasing m as is reflected in the constellation diagrams all of which consider a SNR of 11 dB

starting with 20-CAP in Fig. 5(a), 10-CAP in Fig. 5(b), 5-CAP in Fig. 5(c) and finally 2-CAP and 1-CAP, both in Fig. 5(d). The BER is presented as a function of the energy-per-bit to noise power spectral density ratio E_b/N_o. The BER target is selected to be 10^{-3}, which is slightly lower than the International Telecommunication Unions (ITUs) recommended error floor (3.8×10^{-3}) when using a forward error correction (FEC) with an overhead of 7%.

Fig. 5(a) illustrates that the BER performance of the vast majority of subcarriers approaches the theoretical BER limit for 16-QAM systems, with only a few subcarriers ($s = \{19,\ 20\}$) failing to converge to the theoretical limit. This is attributed to the following reasons:

1) The limited frequency response of the LED means the first half of the subcarriers $s = 1 : 10$ are not affected by the attenuation introduced by the LED low-pass filter; they are within the modulation bandwidth and hence have a maximum signal attenuation of 3 dB at $s = 10$.
2) The second half of the subcarriers $s = 11 : 20$ incurs an additional E_b/N_o power penalty of several dB (approximately $\sim 1 - 3$ dB) in the best case, and failure in the worst cases, as can be seen for $s = 19$ and 20.
3) In the worst case this is because an ideal low-pass filter is used and hence a roll-off of 20 dB per decade is expected. So between $s = 10$ and $s = 20$, the attenuation should be roughly 20 dB and hence significantly degraded performance is shown at $s = 20$. This is also reflected in the constellation diagrams shown inset at $E_b/N_o = 11$ dB, for cases $s = 1,\ 18,\ 19$ and 20, showing a continual degradation.

Fig. 5(b) illustrates the BER performance of a 10-CAP link under the same operating conditions of $f_c = 0.5$. A very similar profile to 20-CAP can be observed, however some very discrete differences between the two cases can be found; the most important is a slight power penalty for the best performing subcarriers $s = 1,\ 2,\ \ldots,\ 8$ of 0.5 to 2.5 dB in comparison to the theoretical performance of 16-QAM. Recalling that the 10-CAP subcarrier bandwidth requirement is twice that of 20-CAP, this slight power penalty is because of the attenuation of the low-pass filter, since a larger attenuation acts on the subcarriers due to the additional bandwidth requirements. This is reflected in the constellation diagrams shown inset for $s = 1,\ 8,\ 9$ and 10 for $E_b/N_o = 11$ dB.

Next, in Fig. 5(c), the same effect as the previous cases can be observed for 5-CAP with an exaggerated power penalty in comparison to the 16-QAM theory which has increased to ~1.5 dB in the best case ($s = 1$) and 3.5 dB in the worst ($s = 3$). Larger subcarrier values fail due to the large attenuation observed as expected and once more this is reflected in the constellation diagrams inset. Finally, the results are essentially confirmed in Fig. 5(d), where both 2-CAP and 1-CAP fail to meet the BER target in the E_b/N_o range considered. It should be noted that the remaining fc values do follow the same trend but are not reported here due to space considerations.

B. Adaptive Bit-Loading within Bandlimited m-CAP

One advantage of m-CAP that has not been explored so far in this article is the possibility to change adaptively the order of the modulation format to suit a given system, based upon the measured signal to noise (SNR) values at the receiver. This technique is called adaptive bit-loading and is well known and widely reported for OFDM based systems [1]. To provide a brief overview, the same block diagram as proposed in Fig. 2 can be implemented but the process starts with the lowest modulation constellation/format of binary phase shift keying (BPSK). The principles of transmission are exactly the same as described previously, however at the receiver a BER measurement is not made in a symbol-by-symbol manner as has been done so far in this work. Instead, the root-mean square EVM of the received BPSK constellation is measured and the SNR is extracted based. The measured SNR values are compared with the known SNR values, considering a target BER, for every order of M-QAM and the maximum possible number of bits/symbol are loaded into each subcarrier in order to improve the spectral efficiency of the system, and avoid errors in subcarriers where the SNR is insufficient. As always; this comes as a trade-off with hardware complexity as the adaptive algorithms will require resources within both the transmitter and receiver.

We implemented such an adaptive m-CAP system based on the adaptive bit-loading technique for $E_b/N_o = 10,\ 20\ and\ 30$ dB for every value of f_c and the results are illustrated in Fig. 6. For the system exhibiting higher E_b/N_o of 30 dB, we found that spectral efficiencies (b/s/Hz) can approach slightly short of 10 b/s/Hz in the case of $f_c = 0.9$, as the vast majority of subcarriers can be loaded with higher order values of M-QAM, thus allowing a high throughput link to be supported. As expected, the spectral efficiencies decrease for decreasing values of f_c. The decrease is approximately linear across the range of m. It is clearly indicated in the 30 dB case, that high spectral efficiencies between ∼8 – 10 b/s/Hz can be achieved when using $m \to 20$. However, the improvement shown for lower values of m could be considered marginal when reflecting on the additional hardware complexity that arises from high values of m. For example $m = 10$ can achieve spectral efficiencies within the range of ∼9 – 6 b/s/Hz for $f_c = 0.9 - 0.1$, respectively and it appears that an asymptotic level can be found in each case, where limited improvement is available, even as m tends to a very large number. This is supported by the 20 dB case, which shows a similar trend. The spectral efficiency is much more consistent with less variation over a wider range of m, implying that the asymptote is reached earlier. For the 10 dB case due to noise restrictions no improvement in spectral efficiency can be found for any value of m.

Fig. 6 Spectral efficiencies of the m-CAP systems considering five degrees of bandlimitation; spectral efficiencies up to ∼10 b/s/Hz can be achieved with sufficient SNR at a BER of 10^{-3} in this case

Finally, in comparison with the literature, the predicted spectral efficiency of ∼10 b/s/Hz is significantly higher than that already achieved experimentally, with the maximum state-of-the-art efficiency reported at 6.25 b/s/Hz in [15], to the best of our knowledge. Thus, m-CAP theoretically offers significant improvements in the transmission speeds available.

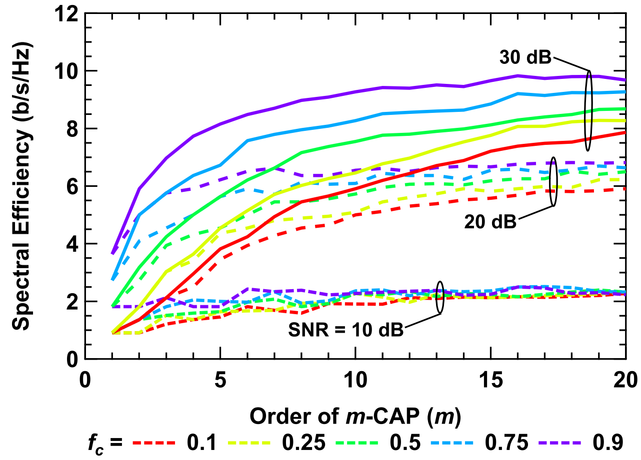

Fig. 6. Spectral efficiencies of the m-CAP systems considering five degrees of bandlimitation; spectral efficiencies up to ∼10 b/s/Hz can be achieved with sufficient SNR at a BER of 10^{-3} in this case

IV. Future Outlook and Conclusions

Here we have shown the considerable potential for m-CAP systems in a bandlimited VLC environment, where higher spectral efficiencies can be achieved. However, the only way to achieve this performance is to use the adaptive bit-loading techniques as outlined here.

Here we have provided the first deep insight of this advanced modulation format and illustrated the potential improvement attainable with this scheme. If m-CAP were to be adopted in VLC systems, further investigation is required. The next stage in the theoretical work is to examine the impact on the link considering the LED non-linearity. In parallel to the enormous potential outlined here by simulations, we are finalizing an experimental test-bed to support our simulations. There is currently no evidence in the literature that reports an experimental m-CAP VLC link. It would be of the upmost importance in the next step to examine the performance of 1-CAP and m-CAP in terms of BER performance for a series of experimental measurements.

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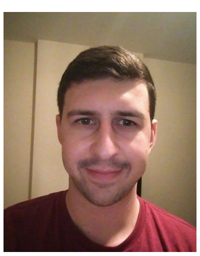
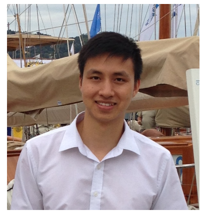


Paul Anthony Haigh received the PhD degree in the area of organic visible light communications from Northumbria University in 2014, publishing over 20 scholarly articles including 13 articles in high ranking journals such as IEEE Journal on Selected Areas in Communications, Optics Express, IEEE Communications Magazine and IEEE/OSA Journal of Lightwave Technology. Between 2010-2011 he held the prestigious Marie Curie Fellowship at the European Organization for Nuclear Research (CERN) where he worked on the optoelectronic links in large hadron collider experiments. In 2010 Paul received the BEng(Hons) degree in Communications Engineering from Northumbria University. Currently, he is a Research Associate within the High Performance Networks group at the University of Bristol working on the EPSRC TOUCAN project. His research is focused on real time seamless, transparent and adaptive and programmable interfaces between wireless and wired multi-technology networks.



Son Thai Le received the Master of Engineering (M.E.) degree with highest distinction from Southern Federal University of Russia in 2012. He joined Aston Institute of Photonic Technologies (AIPT) as a PhD student in January 2013. His research mainly focuses on coherent optical orthogonal frequency-division multiplexing (CO-OFDM), fiber nonlinearity mitigation techniques and visible light communication.

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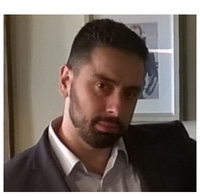

Elias Giacoumidis is currently with Aston University Institute of Photonics Technologies group (previously working at Telecom Paris-Tech and Athens Information Technology). His research focuses in key modern digital signal processing (DSP) algorithmic techniques, such as OFDM/Fast-OFDM, Nyquist-WDM, and fiber nonlinearity DSP compensation techniques, such as Volterra-based nonlinear equalizers (NLEs), digital back-propagation, artificial neural networks based NLEs and adaptive loading algorithms, for next-generation data centers, radio-over-fiber systems, and core/passive optical networks. His research work has resulted in $>$60 papers (380 citations) that have appeared in high quality peer reviewed journals and top international conferences.

Pep Canyelles-Pericas received the Electrical Engineering degree from the Barcelona College of Industrial Engineering EUETIB- Technical University of Catalonia UPC-BarcelonaTech, Spain, in 2006. He also obtained a BEng Electrical and Electronic Engineering (Hons) degree in 2006 from the Northumbria University, UK, through a student exchange programme. He continued his postgraduate obtaining an MSc in Engineering Management (Distinction) by the University of Sunderland in 2008. After finishing this he worked as a project engineer for a SME in Newcastle, UK, for one year. In 2009 he joined the Institute of Cross Disciplinary Physics and Complex Systems IFISC- at University of the Balearic Islands, Spain, as a research engineer, specialising in electronic prototyping and PCB design, where he stayed until September 2012. Then he joined the Northumbria University as a PhD student working in the field of nonlinear control and chaos synchronisation applications. His research interests are observer design and chaos communications.

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